Plasticity-driven Damage Detection using Lamb waves for Stiffened Plate

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Abstract: The process of implementing a damage detection strategy for aerospace, civil and mechanical engineering infrastructure is referred to as structural health monitoring (SHM). Aerospace structural components such as fuel tanks, wings, etc. are often comprised of substructures that consist of plates with integral stiffeners. The use of guided waves for stiffened plate becomes increasingly difficult as the geometric complexity of the structure increases. In this paper, a transient dynamic finite element simulation of Lamb waves with piezoelectric transducers for damage detection in integrally stiffened plate structures is carried out. Transient dynamic finite element simulations using coupled field elements on the commercial finite element code ANSYS 9.0 platform were used to model both the structure and transducers. The plasticity damage zone is produced by reducing the material stiffness. A time reversal imaging method is adopted to detect and locate the damages in the plate. The results of the numerical simulation demonstrate that the approach can detect the stiffened plate structural damage.
Keywords: Integrally stiffened plate, Damage detection, Finite element analysis, Piezoelectric wafer active sensor, Lamb wave, Time reversal theory

Introduction

Stiffened plates are extensively used in most industries such as the aeronautic and automotive industry, because of their light weight and desirable stiffness in the designed direction. However, cyclic work loads and unpredictable collisions may cause possible plastic zone and other damages which severely decrease the structure's performance. In order to respond to any possible damage leading to failure of the structures, damages should be detected, evaluated, and if possible monitored, even though the structures are in services [1]. During the last two decades, increasing resources have been put into the development of built-in damage detection systems [2]. A promising damage detection method is the active system based on the propagation of Lamb waves [3]. Lamb waves utilized in SHM are excited and sensed by piezoelectric wafer active sensors (PWAS). Lamb waves, which are elastic guided waves propagating in thing wall structures with free surfaces, have been well studied and widely used in damage detection [4]. In recent years, a significant amount of research on the modeling and analysis has been carried out to further understand the properties of Lamb waves excited by piezoelectric transducers [5].

The Lamb-wave time reversal method is a new and tempting baseline-free damage detection technique for SHM. With this method, certain types of damage could be detected immediately without prior baseline data [6]. The concept of time-reversal invariance was firstly introduced from optics to acoustics by Mathias Fink and his colleagues, and attention has been paid to time reversal method to compensate the dispersion of Lamb waves and to improve the signal-to-noise ratio of propagating waves [7, 8]. Time reversibility of Lamb waves and its tuning effect were further studied by Victor Giurgiutiu and his colleagues [9]. Recently, imaging process based on time reversal theory was investigated to detect damages in composite plates by Yuan Shenfang and her colleagues [10].

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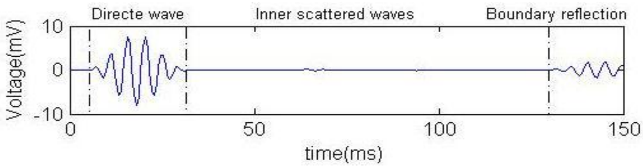
Time reversal imaging method

Time reversal method presents itself as good way to detect structural defects as a baseline free inspection technique, which means, different from traditional SHM method, this one does not need pristine data of the structure to make diagnosis. Time reversal process is achieved by Time Reversal Mirrors (TRM). This procedure could be reasonably explained in two steps. The first step may be called the ' Recording step ', and the second one may be called the ' Time reversing and Re-emitting step '. Firstly, a source send out an excitation *F(t)* which travels within the medium and a set of sensors (TRM) will respectively record the signals arriving at each of them as $G_i(t)$. Secondly, the signals recorded are reversed in time domain as $G_i(-t)$, and re-emitted back into the medium simultaneously by the sensors (serving as actuators now), which means with digital recording, the last sample in the series becomes the first to be played back. The re-emitted waves will retrace the propagation path, get re-compressed, untangle their distortions, and re-focus onto the original source point as *F(-t)*. Thus, the excitation signal is reconstructed by this re-focusing and converging process.

Lamb waves monitored by the sensors can be mainly separated into two parts in time domain: waves directly come from the source, and those from scatters or boundaries. A typical signal sensed by an active sensor is shown in Fig. 1.



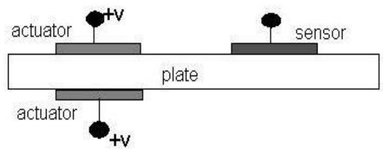


Fig. 1 Typical signal sensed by one sensor

Fig. 2 Actuator/sensor function group

As the signal coming directly from the original source and those from the scatters often mix up with each other, a sensor is put in the vicinity of an actuator to overcome this problem. Thus, the sensor will record the original signal immediately after the excitation, and allows for a comparatively long elapse of time for the scattered signals to be distinguished from the original one. The actuator/sensor pair array arrangement in this study is presented in figure 2. This imaging method also requires a single mode inspection wave to achieve good result. Since pure S0 or A0 mode excitation is hard to be achieved by a single actuator, in this particular discussion the double-sided installation was chosen to permit symmetric and antisymmetric excitation. Thus, axial and flexural waves could be selectively generated. In this paper, pure S0 Lamb wave mode is excited by applying in-phase excitation signals onto both actuators.

With the function group array arrangement, the separation of excitation and scattered signals can be achieved by using a time window function. A rectangular time window is adopted to separate the scattered signals. The time window function could be expressed as:

$$f_w = \begin{cases} 0 & 0 \le t < t_1 \\ 1 & t_1 \le t < t_2, \\ 0 & t_2 \le t < t_3 \\ 1 & t_3 \le t < t_4 \\ 0 & t \ge t_4 \end{cases} \quad t_1 = t_0 + \frac{l_{as}}{c_g} + L, \quad t_2 = \frac{l_{ad} + l_{sd}}{c_g}, \quad t_3 = \frac{l_{ad} + l_{sd}}{c_g} + L, \quad t_4 = t_0 + \frac{l_{ab} + l_{sb}}{c_g} \tag{4}$$

where t_1 is the end time of the wave coming directly from the actuator; t_2 is the beginning time of the reflection from designed geometric change, t_3 is the ending time of the reflection from the designed geometric change, t_4 is the beginning time of the boundary reflection. t_0 is the beginning time of the excitation signal; c_g is the group velocity of the selected mode Lamb wave; l_{as}, L, l_{ab}, l_{sb}, l_{ad}, l_{sd} are the distance between the actuator and sensor, the length of the excitation signal, the distances between the nearest boundary to the actuator and the sensor, the distance between the actuator and the designed geometric change, and the distance between the sensor and the designed geometric change, respectively.

According to time reversal theory, after the reversed signals are sent back, they will retrace the propagation path and self-focus on the source point and the energy will also converge on the source location. In this damage imaging method, the scatters in the structure, including damage, stiffener and boundaries, are considered as the second sources during Lamb wave propagation. So after being re-emitted, the reversed signal will self-focus on the scatters. The amplitude of waves at the focusing location is much higher than other points where signals randomly overlap. An image can be constructed by relating the contrast at a particular pixel to the amplitude of the wave [11]. The damage locating and imaging process could be achieved by creating a digital image with the time reversal algorithm below. Consider the distributed PZT array bonded in the monitored area consisting of N pairs of active actuators/sensors. The contrast S at a particular location or imaging pixel (i,j) can be expressed as:

$$s(i,j)=\sum_{m}^{N} A_m f_w(t_{mij}) f_m(t_{mij}), \quad m=1,2,\ldots,N$$
$$t_{mij}=\frac{R_m^a+R_m^s}{c_g}, \quad A_m=\frac{10}{\max_m |f_m|} \tag{5}$$

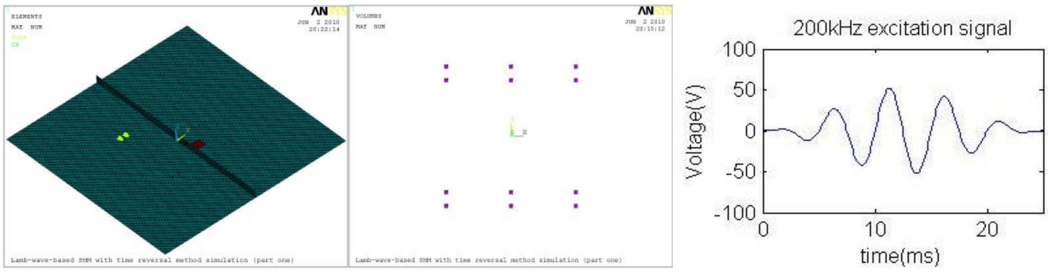
where $f_m(t)$ denotes the received scattered signal by sensor m due to the excitation of actuator m. t_{mij} is the propagation time of the Lamb wave from the actuator to the imaging pixel (i,j) and then to the sensor. Parameters R_m^a and R_m^s stand for the distance from the imaging pixel $S(i,j)$ to senor m, and the one from the imaging pixel $S(i,j)$ to actuator m respectively. C_g represents the group velocity of the propagating wave. A_m refers to the appropriate aperture weight to each function pair, which compensate the performance difference among the various actuator/sensors pairs. Since the excitation is a five-cycle Hanning window modulated sine signal, the imaging result is speckled. An envelope curve method is adopted to process the received signals, which will present the energy distribution character of these signals in time domain.

Damage Detection and Localization in Stiffened Plate

In this paper, a transient dynamic finite element simulation of Lamb wave with piezoelectric transducers for damage detection in an integrally stiffened plate is carried out. The stiffened plate is shaped at 1000mm*1000mm*4mm and a stiffener shaped at 1000mm*40mm*1mm is vertically integrated in the middle of the plate. The plate was instrumented with a surface bonded array of eighteen $8\times8\times0.2\text{mm}^3$ piezoelectric transducers.

Numerical simulations of the wave propagation process were performed using the commercially available finite element code ANSYS. The stiffened plate specimen was modeled using two-dimensional four-node structural shell element (SHELL63) and the three-dimensional coupled element (SOLID5) was used for modeling the piezoelectric sensors. Voltages DOFs were coupled for the nodes of PZT sensors at top and bottom surface to simulate the electrodes. The plate is free-free. The discretization process of the stiffened plate specimen used 62500 elements. The FEM mesh was particularly densified in the plate, where more than 6 FEM nodes per Lamb wavelength were guaranteed to ensure simulation precision. The local distributed damage as 90% stiffness reduction in 100 elements was considered. This represents a square of the size 40mm*40mm, which is 0.16% of the total plate surface. The finite element model of stiffened plate, the location of damage zone and the PZT active sensors are illustrated in Fig. 3 (a) and (b).

The Lamb waves are excited by applying voltage to the top nodes of the actuator. The applied excitation is in the form of a wave packet (5-cycle sine modulated by the Hanning window) with 100 v p-p. The main frequency of this packet is 200 KHz, as shown in Fig. 3 (c).



(a) (b) (c)

Fig. 3 Finite element model, actuator/sensor pairs array and the excitation signal

In this simulation, there are six actuator/sensor function groups forming a sensing array. Each function group works independently to excite pure S0 mode Lamb waves and record the response of the structure. The actuator/sensor function groups work one after another from the first group to the sixth one. These signals are processed with time window, removing the direct waves, the stiffener reflected waves and the boundary reflections. An envelope curve method is adopted to overcome the imaging speckle problem. And then, the signals are time reversed with the imaging algorithm discussed above.

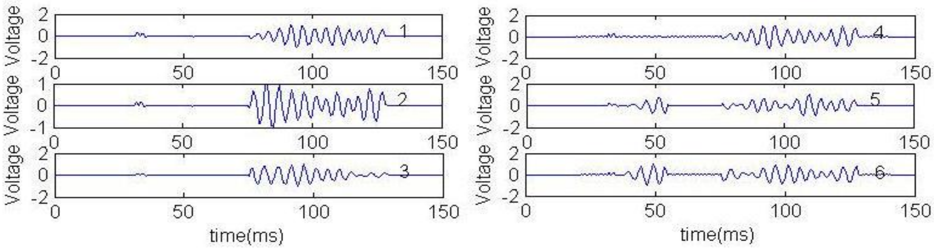


Fig. 4 Normalized signals of actuator/sensor function groups after time window function

Examples of the corresponding time domain signals of six active PZT sensors are shown in Fig.4. Fig.5 shows the enveloped inner scattered signals after spline interpolation and normalization. The stiffener scattered waves and boundary reflections are removed from the signals, and the energy distributions of the waves in time domain are illustrated.

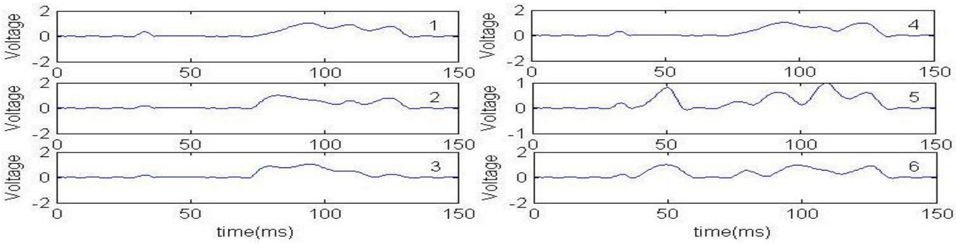


Fig. 5 Envelope curve of the signals

Four simulations are carried out to demonstrate the capability of the imaging method. Firstly, an intact stiffened plate is examined. And the imaging result is shown in Fig. 6. It is obvious that the waves overlap each other randomly with out high value pixel. In this part, the stiffener scattered waves are not removed, and a straight line could be observed in the middle of the plate, which is the image of the stiffener. But since the waves focus on different sites along the stiffener, the pixel values of the stiffener image are not very high. This image indicates no damage zone in the stiffened plate, which matches the intact situation.

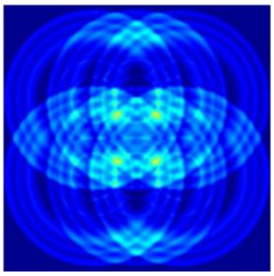
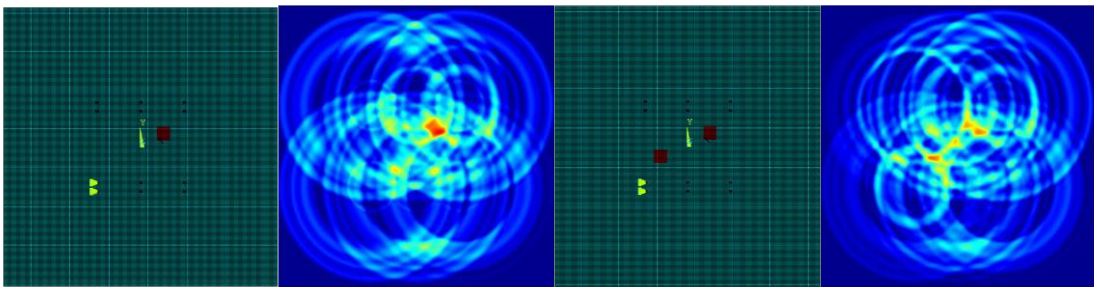


Fig.6 Time reversal imaging of an intact plate

In the second simulation, a damage zone displayed in red in the finite element model is created in the upper right area of the stiffened plate, and the stiffener is in the middle across it. To achieve good imaging result, stiffener scattered waves are removed from the signals. The finite element model and imaging result are shown in Fig.7 (a). A high pixel value area appears in the digital image, which represents the converging and focusing phenomenon of time reversal procedure. Its location agrees well with the damage zone created in the FEM. Without losing generality, a third simulation is carried out when there exist two damages at the same time. The two damage zones displayed in red, are created in the upper right and lower left area of the stiffened plate. The FEM and imaging result are shown in Fig.7 (b). The locations of the high pixel value areas accord with the created damage zones. In these two simulations, stiffener scattered waves are all removed, so the stiffener is not revealed.



(a) (b)

Fig. 7 Locations of the damage zones in finite element model and the imaging results

In order to illustrate the influence of the stiffener scattered waves, signals from the one-damage experiment are processed maintaining the stiffener scattered waves with a different time window which only remove the direct waves and boundary reflections. The imaging result is presented in Fig. 8.

It can be observed that pseudo-focus happens when stiffener scattered waves are not removed. These pseudo-focusing points are caused by the overlying of the stiffener scattered waves and other wave components. Compared with Fig.7 (a), the forth simulation demonstrates the necessity of removing scattered waves from the designed geometric changes. These results suggest that the PZT active sensor array with the time reversal imaging methodology is able to effectively detect and locate the distributed plasticity-driven damage modeled by stiffness reduction.

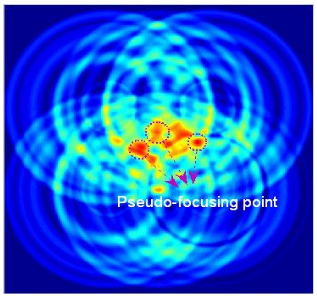


Fig. 8 Image with stiffener scattered waves and pseudo-focusing point

Concluding remarks

In this research, we developed a full multiphysics finite element simulation using coupled field elements for the analysis of Lamb-wave-based damage detection of stiffened plate structure using piezoelectric transducers. The time reversal imaging technique of Lamb waves is used to locate and reveal damage in the stiffened plate. This method of this study can be easily extended to practical geometries such as stiffened or riveted plate-like structures.

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